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Review

Sunflower: From Cortuso's Description (1585) to Current Agronomy, Uses and Perspectives

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Abstract: The sunflower was introduced in Europe (in Spain) in the 15th century, and later in Italy in the second half of the 16th century by Giacomo Antonio Cortuso who was the head of the Botanical Garden in Padua. He and Andrea Mattioli published a detailed description of the species. The sunflower was mainly used for ornamental and medicinal purposes in the following two centuries. In the early 1800s, its cultivation area expanded as a consequence of two new, divergent uses and breeding programs: oilseed production and seed consumption. Nowadays, sunflower is cropped for many uses, mainly food, feed, and biodiesel. Beyond the global interest in this crop, it is extremely difficult to predict its cultivation and productivity in the short/medium term because of the current geopolitical and climate change scenarios. In this last perspective, sunflower cropping should foresee the integration of (i) crop breeding for improving quali-quantitative traits and biotic and abiotic stress tolerance; (ii) agronomic practices to increase the resilience of this crop through anticipated sowing dates and scheduled irrigation according to its phenological phases; and (iii) exploration of new cultivation areas towards higher latitudes.

Keywords: *Helianthus annuus* L.; oilseed market; climatic change scenario; geopolitical crisis; biodiesel; animal feed

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1. Cortuso and the History of the Sunflower (*Helianthus annuus* L.)

The genetics and morphology of the current-day sunflower (*Helianthus annuus* L.) result from a multi-national and inter-continental effort that has stretched over thousands of years. However, the major changes only occurred in the last century. The species is native to North America, where it has long been grown by indigenous tribes. Starting from multi-headed populations, artificial selection led to the current single-stemmed genotypes with a large inflorescence (*capitulum*) carrying a great number of oil-rich achenes.

After the discovery of the Americas by Christopher Columbus, large amounts of sunflower seeds were gathered by the first Spanish explorers and sailed to Europe, starting from the beginning of the 15th century. The first seeds arrived in Spain in 1510 [1] thanks to Francisco Hernandez Giron [2]. Although the many uses, including oil production, were already known by native Americans, Europeans exploited the plant almost exclusively for ornamental reasons and its anti-inflammatory properties for two centuries. Some records demonstrate the use of sunflowers by the native tribes for human nutrition (e.g., roasted achenes) and non-food uses, such as sunscreen or as the basis for a purple dye for skin, hair, and textiles.

As reviewed by Putt [3], after its introduction in Europe in the 18th century, the sunflower was introduced into Russia by Peter the Great [1]. In the beginning, it was grown mainly as an ornamental plant, as in other parts of Europe, but the literature mentions cultivation for oil production as early as 1769 [4]. During the 18th century, the use of sunflower oil became very popular in Europe, particularly with members of the Russian Orthodox Church because sunflower oil was one of the few oils that was not prohibited during Lent [5].

In Italy, the first representation of the sunflower occurred in 1517 in the frescos of 'Loggia di Psiche', Villa Farnesina in Rome, painted by Giovanni da Udine. Moreover, other drawings of sunflowers, named '*Chrysantehemi Peruviani maximus flos*', were made by Aldovandi in the second half of the 16th century [2].

In Italy, the first notice of the presence of sunflowers came from Giacomo Antonio Cortuso, who became the head of the Botanical Garden of Padua in 1590. Although he had graduated in medicine, his greatest passion was botany, as demonstrated by the numerous new plant species he discovered and classified. Cortuso cultivated sunflowers that he carefully studied to characterize the main plant traits including achene quality. A mention of his observations was reported in his famous letter addressed to the botanist Andrea Mattioli, who published it in a book in 1585. In that book, the sunflower was addressed with many names, including Maximum Plant, Royal Crown, Jupiter's Cup, Indian Sun, and Plinian Bellide, ideally referring to the height of the plant, the shape of the inflorescence, or its origin, and similarity to the Common Daisy (*Bellis perennis*) (Figure 1). Other curious names were Trumpet of Love and Rose of Hierico.

Figure 1. Drawing of a sunflower plant as reported in a letter from Cortuso to Mattioli (1585). https://archive.org/details/bub_gb_H-bmaXwpdr8C/page/n31/mode/1up. (Accessed on 5 August 2022).

Together with the letter, Cortuso sent Mattioli a few sunflower seeds, describing the elevated growth rate of this plant under high temperatures and its relatively short life cycle of about six months. The plant was described as annual, already lacking stem branches, carrying just one inflorescence that surprisingly exhibited heliotropism until seed production, and highly visited by bees. Various products were reported by Cortuso as extractable from the plant, such as an aromatic resin from stem incisions. The main observation about oil production was related to its pleasant taste. He also reported that the stem was edible following roasting and after removing the dense outer hairs: "*when seasoned with oil and species the flavour was described better than mushrooms, asparagus and thistles*". Raw chewed leaf petioles were also reported as an excellent source of juice, while the mature stems, picturesquely assimilated to Hercules' club, can be efficiently used for firing.

Cortuso described sunflowers as having an inflorescence with a diameter greater than that of a human head; this trait has been controversially selected over the last decades. After a period with a desire for plants with a large inflorescence diameter, the discovery of the centripetal flow of the plant sap in the inflorescence shifted this desire to smaller diameters to avoid sterile zones in the central part of the capitulum. The plant height reported by Cortuso in soft soil was very tall, i.e., 120 geometric palms (about 9 m). All the breeding programs have led to a progressive reduction of plant height, which has gone down to 1.5–2.5 m in modern hybrids for achene production.

2. Sunflower Breeding and Implications on the Dynamic of the Cropped Surface

The cultivation area of sunflower expanded when the demand for its oil greatly increased in the early 1800s, with two divergent uses and breeding programs: oilseed production and seed consumption. In Russia in the late 1800s, a great number of varieties referred to as the Mammoth Russian were selected; some of them showed a maximum inflorescence diameter of 0.5 m.

A boost in sunflower cultivation occurred at the beginning of the 1900s, with the development of industrial oil processing and the production of protein-rich by-products suitable for animal feed. In Russia, the most important breeding work was carried out by Vasilii Stepanovich Pustovoit starting in 1960. The work was carried out, until his death in 1972, through trans-pollination to combine multiple favorable traits otherwise found in different varieties. New breeding programs started in the USA and Canada much later, when the best Russian open-pollinated variety Peredovik was already licensed in various countries, including Canada. This variety had desirable traits such as a high oil content (about 45%) and small seeds and was suitable for bird and duck feeding. The oil content is a highly heritable trait, and modern varieties commonly show an oil content of 50%; a maximum value of 60% is rather difficult to combine with other useful characteristics. On the contrary, how breeding can independently increase the protein content of sunflower achenes is still poorly known [6].

Starting from the late 1960s, after pursuing high yield levels and oil contents, resistance to fungal pathogens became another important trait for breeding. This brought about the development of open-pollinated varieties resistant to various races of downy mildew (*Plasmopara halstedii*) [7]. Many ecotypes with downy mildew resistance strangely come from dry or desert areas (Texas) where no downy mildew is observed. As regards Phomopsis Stem Cancer (*Diaporthe helianthi*), strong quantitative trait loci for downy mildew resistance were identified in Serbia after the first occurrence of the disease in this country [8] and later in France [9], but phomopsis resistance is still an essential objective of sunflower breeding programs today. Sclerotinia wilt or rot (*Sclerotinia sclerotiorum*) is the most widespread disease of sunflower, and selection for its resistance is limited by the absence of complete resistance, as supported by the identification of numerous QTL in France and Argentine [10,11]. Fortunately, most of the pathogen injuries are currently reduced under climate change and by cultivating sunflowers in drier areas.

These resistances/tolerances to pathogens were preserved even when the first true hybrids were selected as higher-yielding alternatives to open-pollinated varieties—a further development hindered by the self-pollination of the hermaphrodite florets. By implementing a method that allowed cytoplasmic male sterilization, the French researcher [12] changed the way of breeding sunflowers towards the production of true hybrids. Meanwhile in the USA, Kinman [13] discovered a way of switching male fertility back on in the resulting hybrid and made it possible to fully exploit different traits from parent plants. This opened a new age of breeding for the sunflower: its agronomic performances were greatly improved, and the number of commercial varieties customized for different applications and environments substantially increased. Škorić et al. [14] suggested that a target seed yield of 6 t ha^{-1} could be pursued, while 4 t ha^{-1} is a common productivity in central France. However, new challenges in dry environments still have to be addressed. The crossing with *Helianthus argophyllus*, which grows in semi-arid conditions in the USA, has shown promising results [15]. This is an important issue as the increase in seed production has outpaced the increase in the surface areas devoted to this crop, as highlighted by the trend shown in Figure 2.

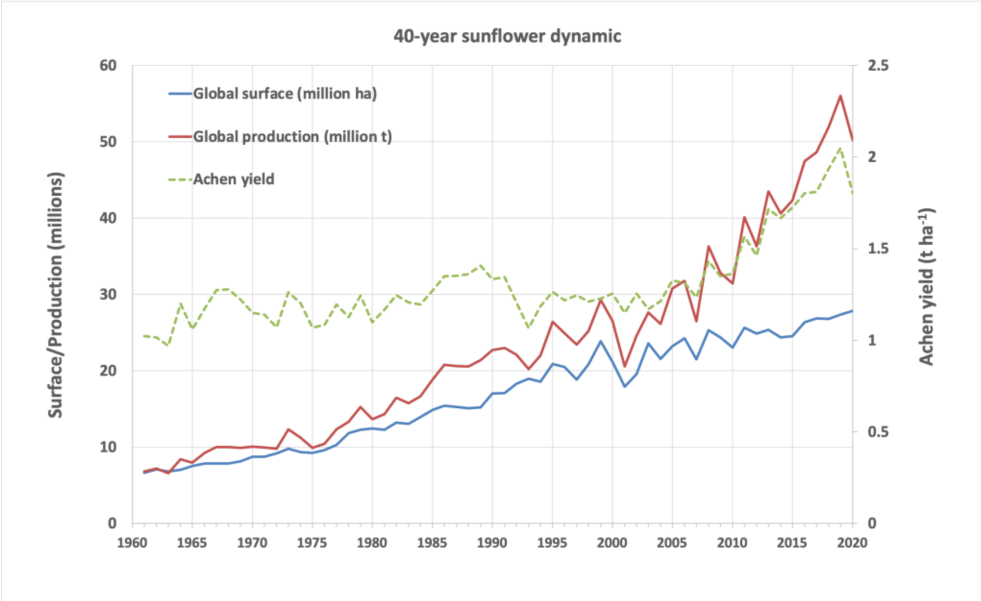

Figure 2. Dynamics of global sunflower cultivation and productivity over the last 40 years. (Data source: FAOSTAT).

Another important objective of breeding was the reduction of plant height using semi-dwarf phenotypes, particularly in the 1980s. The yield of the resulting plants (about 1 m in height) was so dramatically reduced due to impaired vascularization of the *capitulum* that further efforts to reduce plant height were quickly abandoned [16]. Instead, the development of cultivars with a lower achene water content at harvest associated with anticipated maturity has been more successful [17]. Some researchers also thought of introducing stem branching in order to obtain many small inflorescences, but the drawback was asynchronous maturity. An alternative was the Y-branched stem, but it was difficult to apply to all the descendants [18,19].

We are now entering a new age of sunflower breeding in which resistance to some herbicides is at the center of breeding programs. Clearfield types, resistant to the active ingredient Imazamox and other imidazolinones, have greatly improved post-emergence chemical control against most monocot weeds and invasive dicot weeds, such as *Xanthium strumarium* and wild sunflowers. This can also be a valid alternative to pre-emergence herbicides, whose effects are often hampered by low soil moisture. The original Clearfield trait of sunflower—the so-called ImiSun trait—is based on a naturally induced mutation of acetohydroxy acid synthase (AHAS) discovered in 1996 in a wild sunflower growing in a soybean field in the United States [20]. Nowadays, many commercial hybrids contain this trait [21].

A further novelty in weed control appeared in recent years with the Express Sun hybrids tolerant to the active ingredient Tribenuron—a member of the sulfonylurea group—thanks to the combination of two different gene sources (one from the DuPont Chemical company, the other from Kasim Al-Khatib and Jerry Miller's collaboration). Tribenuron efficiently controls many dicot weeds, and partially a few other weeds such as *Cirsium arvense* [22], but is ineffective against grass weeds. The efficacy of Tribenuron on some dicot weeds such as *Ambrosia artemisiifolia* and *Galium aparine* is lower than that of imidazolinones, and Tribenuron has to be used in the early growth stages or in a split application [23]. This has stimulated a particular market, with seeds and herbicides packaged together.

3. Sunflower Cultivation under Climate Change Scenarios

Sunflower is mainly cropped as a spring–summer crop, under rainfed conditions [24]. As a consequence, it is increasingly exposed to the negative effects of climate change, i.e., temperature increase, elevated atmospheric CO_2 concentrations, extreme climatic hazards, and reduced water availability according to projections [25]. Moreover, the sunflower relies on water during flowering and achene filling [26,27].

Within this perspective, different management practices should be adjusted to prevent drought stress, such as anticipating sowing dates (drought escape) [28], providing irrigation water, using osmoprotectants and hormones to improve drought tolerance, breeding drought-resistant varieties, and exploring new areas for cultivation.

Considering that the common practice is to sow sunflowers in March/April in the Mediterranean area, many studies have explored the possibility of anticipating sowing dates by about one month [26,29,30], with positive effects on achene yield. A recent study carried out in Sardinia even explored winter sowing dates [31] showing that achene yield was reduced when the sowing date occurred before late February, probably due to a low accumulation of growing degree days from sowing to anthesis and from sowing to harvest. Additional risks related to anticipated sowing in winter have been identified, such as cold and frost damage, and predation by soil insects, slugs, or birds [32].

An early sowing date combined with irrigation could improve the drought escape strategy [32], as confirmed by Giannini et al. [31]. These authors used EPIC to simulate the effect of watering sunflowers from 20 days before flowering up to flowering under four different sowing date scenarios (10th January, 10th February, 10th March, and 10th April). The amount of supplied water (~160 mm) supported achene yields close to potential ones even for the winter sowing dates (January and February).

Sunflowers can rely on irrigation water and drought stress can hamper their yield components [33]. Göksoy et al. [34] compared 14 irrigation treatments with full or limited irrigation water supplied during critical phenological stages of sunflowers (heading, flowering, milking). They observed higher achene yield and oil yield under irrigated conditions. Moreover, drought stress was avoided during flowering under limited irrigation, as already observed by Browne [35] and Rawson and Turner [36].

Some studies have explored the application of osmoprotectants, growth-promoting rhizobacteria, biochar, and arbuscular mycorrhizal fungi to improve drought tolerance. Hussain et al. [37] explored the exogenous application of glycinebetaine and salicylic acid at the vegetative and flowering stages under water stress. They recorded a maximum number of achenes *per* head after foliar application of salicylic acid at the vegetative stage, while the effect of glycinebetaine application on the number of achenes *per* head was significant during the flowering stage. A few years later, Iqbal et al. [38] tested exogenous glycinebetaine application at the seed and foliar stages and found a positive effect on achene weight when glycinebetaine was applied at the foliar stage. Singh et al. [39] inoculated sunflower seedlings with different growth-promoting rhizobacteria (*Azotobacter chroococcum*, *Bacillus polymyxa)*, alone or in a mixture. The mixture promoted sunflower growth and increased the protein and pigment contents, even under drought stress. Biochar application and arbuscular mycorrhizal fungi may also mitigate the effect of drought conditions on sunflowers [40].

Climate change concerns have currently refocused breeding efforts toward producing plants able to tolerate cold during the vegetative phase and perform better in drought conditions. As regards cold tolerance, considering that base temperatures for sunflower germination range between 3.0 and 6.9 °C [41] and that low and fluctuating temperature regimes can be foreseen with earlier sowing dates, breeding for cold-tolerant genotypes could provide a wider guarantee of success against freezing and chilling stress [32]. As regards drought tolerance, altered head shapes to avoid sunburn, bird damage, and diseases have been selected for, but much still remains to be achieved to develop drought-resistant cultivars. New target traits include improved oil properties, confectionary hybrids with lower oil content, ray and disk flower color changes, and flowering period to better fit markets and climate conditions.

There is a current debate on possible negative side-effects of modern sunflower hybrids on the ability of bees to extract honey. The profitability of sunflower fields for beekeepers is obviously decreasing. Some reports highlight a sharp reduction in sunflower honey production in Italy in the last years, from 20–25 kg (2015–2016) to 7 kg *per* hive (2020). This observation is widespread, and the new hybrids seem to produce a considerably lower amount of nectar *per* floret than old open-pollinated varieties did [42]. Although this first study provides a possible explanation for the mystery of the challenges faced by honey bees when it comes to modern sunflowers, a lot of phenotyping would be necessary for a complete answer, targeting pollen and nectar composition, tubular floret length, etc. [43].

A possible alternative to cope with sunflower productivity and climate change could be to explore new areas of cultivation or increase cropping surfaces in regions in which sunflower is already cropped at a smaller scale. A few years ago, Deppermann et al. [44] simulated the potential yield of oilseed crops, including sunflowers, if the abandoned lands of Ukraine and Russia were cultivated. They showed that net exports could increase up to 18.9×10^6 t by 2030, and constitute 3.5% of global production in 2030. The current unpredictable geopolitical scenario has significantly changed the perspective of using those lands to improve sunflower yields.

4. Sunflower Uses and Market

The sunflower can be related to different economic chains. It is used in the food industry for both oil and confectionary seed production, for biodiesel production, while its residues or other plant parts can be valorized differently.

4.1. Sunflower Market Development

Sunflower is now ranked as the fourth most important oil crop in the world, after palm, soybean, and rapeseed. According to FAOSTAT (2020), sunflower production reached a global level of 50.2×10^6 t in 2020 (global production was 9.9×10^6 t in 1975), while its cultivated area increased from 9.2 M ha in 1975 to 27.9 M ha nowadays. Production has increased more than twice as much as the production area, a sign of the significant impact of three factors: (i) an increasing level of consumer demand, (ii) considerable technical progress in agricultural techniques, and (iii) in the European Union, positive support from the Common Agricultural Policy [45]. However, the trend in sunflower production has stabilized over the past five years, and cultivated land has remained in the 25–27 M ha range every year.

This stabilization process of the production level and of the total harvested area has also been visible in Italy in recent years (Figure 3). Similar results came from the analysis of the average yield (2.44 t ha^{-1}—Table 1), which was much higher than the world average (1.86 t ha^{-1}).

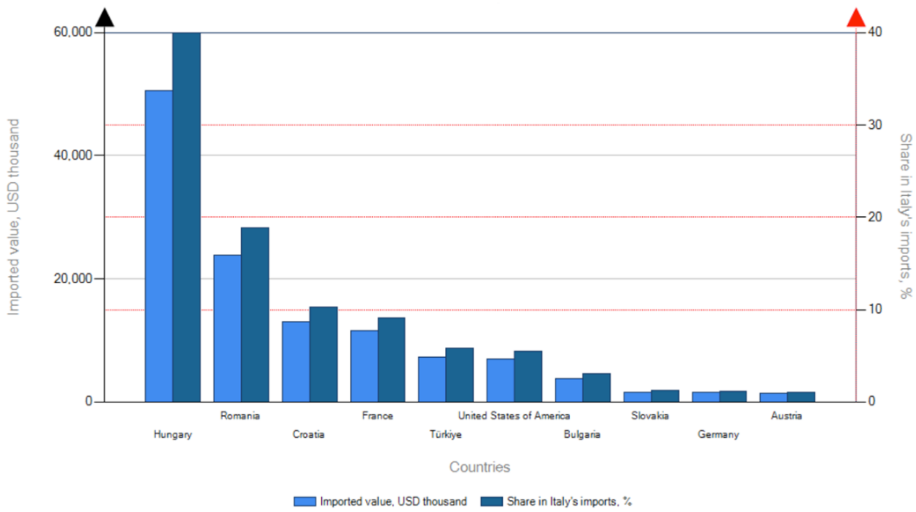

Figure 3. Sunflower seed imported by Italy in 2021 (value (USD 1000) and share of Italy's imports, (%)) (Source: UN COMTRADE).

Table 1. Sunflower annual production, harvested areas, and yields in Italy, 2010–2022. (Sources: FAOSTAT and EUROSTAT.)

Year	Harvested Area (ha)	Production (t)	Yield (t ha^{-1})
2010	100,500	212,900	2.12
2011	118,067	274,414	2.32
2012	111,678	185,494	1.66
2013	127,628	285,233	2.23
2014	111,350	250,377	2.25
2015	114,449	248,007	2.17
2016	110,716	268,331	2.42
2017	114,446	243,671	2.13
2018	103,870	250,460	2.41
2019	118,520	294,730	2.49
2020	122,770	299,880	2.44
2021	116,990	282,400	2.41
2022	109,460	267,931 *	2.45

* Estimated value.

In 2020, Italy was the 18th producer of sunflower seeds in a ranking that saw the Russian Federation and Ukraine dominating the world market with almost the same level of domestic production (13.3 $\times$ 10^{6} t in Russia and 13.1 $\times$ 10^{6} t in Ukraine in 2020) (UN COMTRADE data). These two countries account for more than half (52.6%) of the world seed production (50.2 $\times$ 10^{6} t).

For an appropriate framework of market development analysis, it is important to consider that, as in the case of other food products, sunflower tends to be traded mainly after processing. Compared to other oilseeds, sunflower tends to have a greater amount of processing of raw materials located in the countries of production; only palm oil follows a similar trend, but this is mainly due to the extreme concentration of production in two "specialized" countries (Malaysia and Indonesia) that control 84% of the world production.

With its 150,100 t of sunflower oil production, Italy is 20th in the world ranking (UN COMTRADE, 2019), once again dominated by the Federation of Ukraine and Russia, with similar levels of production and covering 56.1% of the world's supply of sunflower oil (200.5 $\times$ 10^{6} t).

Significant as it is, Italy's domestic supply is far from covering domestic consumption. Italy is an importer of both sunflower seeds and sunflower oil, but with two different models of market development in import flows (Table 2):

- The level of seed import in 2010 (220,715 t) was almost identical to that of domestic production (212,900 t) and gradually decreased to a minimum in the last year of the examined period (2021: 153,350 t);
- Conversely, oil imports increased significantly over the same period (+126%).

In addition, in 2021, Italy imported sunflower seeds from Hungary, Romania, Croatia, and France (Figure 3) and sunflower oil from Ukraine (45.8% of the total imported value), Hungary, and Bulgaria.

As a result of increased Italian imports of sunflower oil, the self-sufficiency rate of the sector gradually declined, and the land footprint of Italian consumption on agricultural land in foreign countries significantly increased (Table 3).

Table 2. Italian sunflower production and import (2010–2021).

Year	Seed Production (t)	2010 = 100	Seed Import (t)	2010 = 100	Oil Import (t)	2010 = 100
2010	212,900	100	220,715	100	251,286	100
2011	274,414	129	228,061	103	204,207	81
2012	185,494	87	214,622	97	282,522	112
2013	285,233	134	249,223	113	286,680	114
2014	250,377	118	176,223	80	410,638	163
2015	248,007	116	159,743	72	369,281	147
2016	268,331	126	225,316	102	454,525	181
2017	243,671	114	222,568	101	550,365	219
2018	250,460	118	224,012	101	609,185	242
2019	294,730	138	237,390	108	658,813	262
2020	299,880	141	159,737	72	589,559	235
2021	282,400	133	153,350	69	567,656	226

Table 3. Domestic consumption of sunflower products and impact on land use (2010–2021).

Year	Production (t)	Seed Import (t)	Oil Import (t) [1]	Domestic Consumption (t)	Land Equivalent (ha) [2]	Land Footprint Abroad (ha) [3]	%
2010	212,900	220,715	195,377	628,992	296,917	196,417	195.4
2011	274,414	228,061	158,773	661,248	284,503	166,436	141.0
2012	185,494	214,622	219,663	619,779	373,143	261,465	234.1
2013	285,233	249,223	222,896	757,352	338,878	211,250	165.5
2014	250,377	176,223	319,274	745,874	331,712	220,362	197.9
2015	248,007	159,743	287,119	694,869	320,665	206,216	180.2
2016	268,331	225,316	353,397	847,044	349,499	238,783	215.7
2017	243,671	222,568	427,913	894,152	419,960	305,514	267.0
2018	250,460	224,012	473,646	948,118	393,201	289,331	278.6
2019	294,730	237,390	512,233	1,044,353	419,966	301,446	254.3
2020	299,880	159,737	458,387	918,004	375,828	253,058	206.1
2021	282,400	153,350	441,357	877,107	363,360	246,370	210.6

[1] t of seed-equivalent converted using a conversion rate of 1.398 kg of sunflower seeds = 1 L of oil and 1 L of oil = 0.00092 t of oil. [2] Calculation based on average annual yields of Italian farmlands. [3] Extra farmland needed for producing the amounts of imported sunflower seed and oil. Sources: Source: UNCOMTRADE and FAOSTAT.

A key factor in the development of domestic demand for sunflower oil (particularly for food uses) was the need to replace palm oil because of its alleged poor nutritional characteristics (a very questionable criticism—[46]) and the environmental impacts in producing countries. In fact, palm oil production has grown at an impressive rate in the last two decades (from 11.45×10^6 t in 1990 to 43.87×10^6 t in 2009, to reach 72.94×10^6 t in 2012), partly due to the competitiveness of its price on the international market compared to the main competitors (Figure 4).

A significant component of the increase in palm oil exports, including Italy, is associated with the issue of embodied deforestation [47,48]. Table 4 presents the preliminary results of an evaluation of deforestation embodied by the macroeconomic sector linked to the import of palm oil by Italy and three other countries of the European Union (G. Bausano, M. Masiero and D. Pettenella, personal communication).

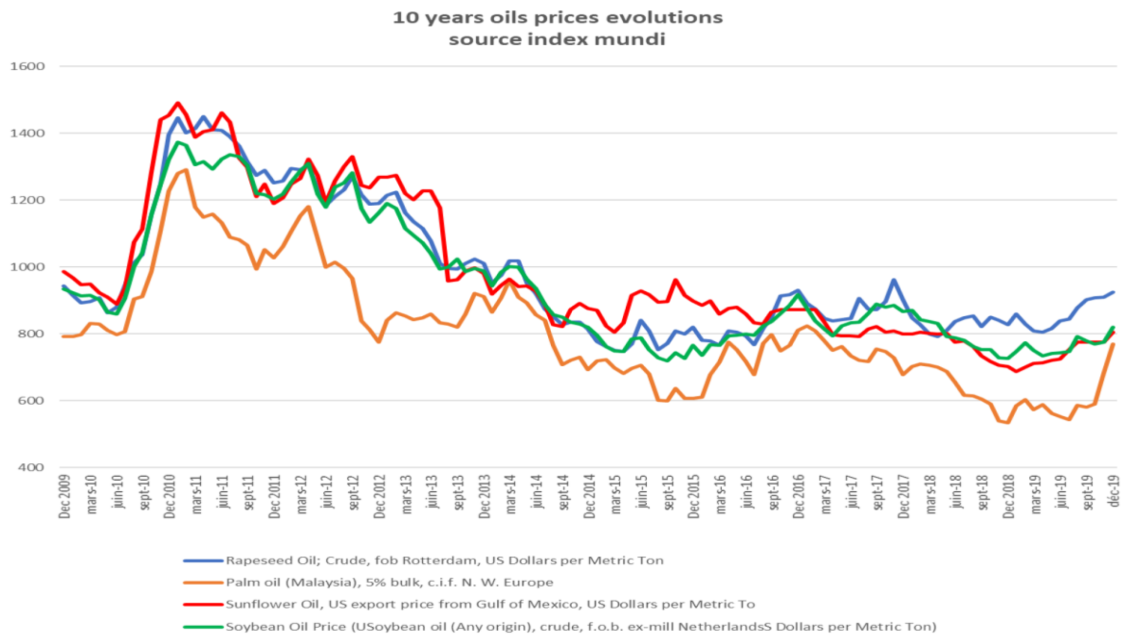

Figure 4. Evolution of vegetable oil prices (2009–2019). (Source: Pilorgé [49]).

Table 4. Total annual and mean annual embodied deforestation by the macroeconomic sector (2002–2019). Source: our elaboration based on UNCOMTRADE data.

Total Annual Embodied Deforestation *per* Sector (ha)				
Sector/Country	Italy	France	Germany	Spain
Food	42,932	9367	53,124	23,809
Energy	52,593	19,853	12,971	49,970
Oleochemicals	10,193	1215	16,010	6618
Mean Annual Embodied Deforestation *per* Sector (ha Year^{-1})				
Sector/Country	Italy	France	Germany	Spain
Food	2147	468	2656	1190
Energy	2630	993	649	2498
Oleochemicals	510	61	801	331

In recent months, the current market conditions for vegetable oils used by the food, oleochemical, and energy industries have been subject to a major change: on the one hand, the war in Ukraine and Russia's export embargo have increased the price of sunflowers; on the other hand, the perception of the risks linked to the use of palm oil has changed, thanks to the information campaigns of organizations such as the *Unione Italiana per l'Olio di Palma Sostenibile*, among others, and the great availability of RSPO (Roundtable on Sustainable Palm Oil) certified palm oil, already traditionally employed by one of Italy's leading agri-food companies. A new European Union regulation on zero deforestation and forest degradation will soon be applied to six agricultural and forestry products (including palm oil). It will be a new driver of the highly competitive market for vegetable oils. In this context of interactions between conflicting drivers, it is extremely difficult to predict the opportunities for expanding domestic sunflower production. As John Nasbit said, "*The most reliable way to forecast the future is to try to understand the present*".

4.2. Sunflower for Food Consumption

Regarding vegetable oil production, sunflower hybrids are grouped into (i) traditional sunflowers with an oleic acid content of 14–39% of the oil; (ii) mid-oleic acid sunflowers (42–72% oleic acid content, also called NuSun in the United States); and (iii) high-oleic acid sunflowers (75–91% oleic acid). Among these, the high-oleic sunflower is considered the healthiest, contributing to preventing cardiovascular diseases [50], in addition to its extended shelf-life and more stable frying properties [51].

Some sunflower mutants express high-stearic traits on a high-oleic background. They are enriched in triacyglycerols (as in cocoa butter) that can represent a valuable alternative to palm oil [52]. Palm oil offers a series of characteristics making it the reference oil for the food industry because it is cheap, naturally semi-solid at room temperature, and has a long shelf-life. In addition, palm oil has a neutral taste and a smooth texture that can give food products an appealing mouth-feel, and it has a high smoke point that makes it particularly useful as a frying oil [53]. In this context, the new high-stearic–high-oleic sunflower genotypes could be a reliable new source of oil for the food industry [54].

Confection sunflower represents a new market segment, either used inshell (roasted or salted) for snacks, or hulled for baking [49]. Those seeds are a multi-nutritional source of amino acids, proteins, unsaturated fats, fiber, vitamin E, and minerals [55].

In addition to dietary purposes, extracts from plant parts (stem, leaf, root) are used by the pharmaceutical industries, given their content of carbohydrates, phytosterols, amino acids, proteins, and mineral salts [55]; the vegetative parts could be differently valorized and re-used as insulation materials [56], or natural fibers for biomatrices [57].

4.3. Biodiesel Production

The use of large-scale energy crops to replace fossil fuels may prove to be one of the most important agricultural options for reducing CO_2 emissions. However, the environmental benefits are not only related to the use of crops but also to the fact that the crops are grown with extensive practices and reduced inputs (especially fertilizers and pesticides).

Two main products derived from sunflowers can be used as fuel, namely crude oil and its derivative—biodiesel. The potentiality of sunflower for biodiesel production was already revealed in Italy by Bona et al. [58]. In the following years, the choice of the hybrid cultivar was found crucial for productivity [59], while sunflower was already cultivated for biodiesel production in different areas of the world [60,61].

Biodiesel is currently the most commonly used fuel among oil-refining derivatives. Derived from triglycerides by transesterification with mainly methanol, it is a non-toxic biodegradable fuel produced from vegetable oils [62]. About 80% of oil mixed with 20% of alcohol (almost exclusively methanol) react through a catalyst. Biodiesel and glycerin are the final products. They are separated based on their different densities. Biodiesel has a similar viscosity to diesel so it can be an excellent substitute for it. For these reasons, esters have great potential for biodiesel use. Different types of oil from different origins can be used [63–66], but also residues from animal processing [67].

Distinctive features compared to diesel are the absence of sulfur and aromatic compounds, the reduction of particulate matter, and the reduction of greenhouse gas emissions [68,69]. A very important feature is its total biodegradability [70]. Therefore, it is suitable for use in the engines of inland water vessels or heating in sensitive areas. It also has better lubricity characteristics than diesel [71].

In Europe, biodiesel is much more widespread than bioethanol because it can exploit pre-existing technologies and distribution chains [72]. It is generally used in a mixture with diesel fuel by exploiting the intermediate characteristics between the two fuels [73].

Crude oil could fit the needs of low-impact agriculture, as it can be used in medium-sized plants (5–15 MWe), with marine diesel engines or gas turbines to produce heat and electricity [74]. Among vegetable oils, sunflower oil deserves particular attention, as it comes from a crop well suited to our territory as a substitute for corn, requiring few inputs and therefore easy to manage [75]. Table 5 shows the main physico-chemical characteristics of sunflower oil and diesel fuel to compare their properties.

Table 5. Main properties of sunflower oil and diesel. (Source: CTI, 1993.)

Properties	Sunflower Oil	Diesel Oil
Density at 20 °C (kg dm^{-3})	0.92	0.82
Viscosity at 38 °C (cSt)	37.1	2.7
Lower calorific value (MJ dm^{-3})	32.9	35.8
(CN) Cetane number	37	47
(FP) Flash point (°C)	274	68
Solidification point (°C)	−18	

The higher density of sunflower oil compared to diesel oil determines greater hourly consumption for an engine. Compared to diesel, sunflower oil is about 14 times as viscous at 38 °C. This high viscosity affects the injection system, due to the poor atomization of the fuel at the level of the combustion chamber, causing "dirty" combustion which negatively affects the life of the engine. Since viscosity decreases with increasing temperature, it can be reduced by heating the oil before injection or by heating filters, tanks, or pipes before the injector.

The calorific value of sunflower oil is lower than that of diesel: this means higher specific consumption to obtain the same deliverable power. The cetane number (CN) affects cold starting, combustion, maximum pressure, and engine noise. The higher the CN value, the greater the readiness of the fuel for ignition. The optimal range is between 40 and 50 CN, therefore sunflower oil is not very far from it. Vegetable oil has a much higher flash point than diesel, hence safer storage, transport, and handling.

Vegetable oils have considerable variability in the points of solidification: the oil begins to opacify and increases in thickness until it becomes completely solid. This parameter affects the filterability and limits the flow of the fuel: the solid particles suspended in the fluid oil could be captured by the fuel filter and cause its clogging. In this case, it is important to preheat the oil before it leaves the tank or before it enters the injection pump. Based on previous studies, we can say that sunflower oil extracted with the cold system using a mechanical press has physico-chemical characteristics compatible with its use as biofuel in internal combustion engines.

Alongside conventional centralized industrial plants, vegetable oil can be produced in decentralized plants located in rural areas and managed by local farmers. The shorter transport distance is an obvious environmental advantage, and added value for the farmer who has various possibilities: sell the seed produced at the international market price; transform the seeds in an agricultural oil mill, market the oil on the local market and leave the protein cake in the hands of local farmers; directly use the oil produced for agricultural processing and save on diesel consumption.

4.4. Feed Production

Sunflower provides many feeds for monogastrics and ruminants. The major feeds are sunflower seeds, sunflower meal or cake, sunflower hulls, sunflower foliage and crop residuals, and sunflower oil [76,77].

Sunflower foliage and crop residues are used as forage in ruminants' rations. Sunflower foliage can be ensiled. This practice is adopted in areas where the summer season is too short to produce maize grain [78].

Whole sunflower seeds are expensive because of their oil content, so they are mainly used as pet bird feeds. Due to their oil content and their fatty acid composition, particularly rich in linoleic (62–75%) and oleic (16–27%) acids, they could be used to manipulate the fatty acid composition of ruminant meat and milk [76]. The use of sunflower seeds in ruminants' feed resulted in an increased content of conjugated linoleic acids (CLA) and C18:2 omega-6 fatty acids in ruminant products [79].

The seeds are commonly subjected to decortication. This treatment produces two fractions, i.e., the hulls and the dehulled seeds. Sunflower hulls are rich in fiber and have a low nutritional value; they are considered a cheap source of fiber or as bedding [77].

The seeds—dehulled or not—are commonly subjected to oil extraction. Sunflower oil is produced for the human food market and is seldom used in animal nutrition because of its cost. However, sunflower oil can be used in small quantities by the feed industry to reduce the dust level and improve the quality of the pellets [77], or as an additive to manipulate the fatty acid profile and the CLA content of milk and meat [80].

The solid byproduct resulting from oil extraction Is named sunflower meal or cake, depending on whether the extraction was completed using chemical solvents or physical compression, respectively. Sunflower meals/cakes are considered major sources of proteins for livestock. Their nutrient contents are strongly influenced by the genetic variety, the level of decortication, and the level of oil remaining after extraction [77]. On average, dehulled sunflower meal (<5% oil, dehulled) contains 36.6 $\pm$ 1.4% of crude protein, 31.4 $\pm$ 4.8% of neutral detergent fiber (NDF), and 1.2 $\pm$ 0.4% of crude fat. For ruminants, the net energy (NE) contents of sunflower meal are 6.3 and 5.8 MJ kg^{-1} dry matter (DM) for lactation and meat production, respectively [81]. For pigs, sunflower meal provides 6.7 and 7.2 MJ kg^{-1} DM of NE for growth and maintenance, respectively. Compared to soybean meal, sunflower meal (<5% oil, dehulled) contains on average 16% less crude protein, and 41% more NDF, and thus a 30–36% lower NE content. In addition, sunflower meal proteins contain about 3.6% lysine, which is about half the lysine content of soybean meal proteins (6.2 %). However, differently from other oilseeds, sunflower seeds do not contain antinutritional factors, and they are safe for all livestock species without requiring any thermal treatment. Nevertheless, the seeds should be monitored for mycotoxin contamination (particularly aflatoxins B1 and ochratoxin) and pesticide residues [82]. Thus, sunflower meal can be used to replace the more expensive soybean meal, but the amino acid profile and fiber balance should be checked, particularly for monogastrics. For ruminants, the lower lysine content of sunflower meal is of minor importance because the feed proteins are degraded into peptides and ammonia, which are used by the rumen microbes to synthesize microbial proteins rich in indispensable amino acids [83].

5. Conclusions and Perspectives

In the context of climate change and increasing attention to the impacts of agricultural practices on the environment, the sunflower and its diverse features listed in the present article represent a crop that could be promisingly cultivated in many regions of the world. Nevertheless, the cultivated surface is still small, suggesting that more efforts should be made to increase the competitiveness of this crop in terms of quantitative and qualitative aspects. Agronomic research should be focused on the current "yield gap" between attainable and attained yield in real-farm conditions. Further efforts should target breeding programs to meet the diversified products demanded by the market and tailor agronomic protocols to better sustain yield, higher grain quality, and better oil quality. The introduction of new sunflower mutants expressing a high-stearic trait on a high-oleic background could represent a valuable solution to open new market spaces for sunflower oil in the food industry.

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